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Political boundary between Dvāravatī and Ancient Khmer kingdoms: The recognition of ancient frontier networks in Eastern Thailand before the 11th century CE

Patcharaporn Ngernkerd *, Rasmi Shoocongdej, Saritpong Khunsong

Department of Archaeology, Faculty of Archaeology, Silpakorn University, Bangkok, Thailand

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ABSTRACT

This paper examines the nature of the political boundary between the Dvāravatī and Ancient Khmer kingdoms in eastern Thailand between the 7th and 11th centuries CE. Using a theoretical framework based on the Mandala model, this frontier is examined via spatial analyses between the large, rectilinear towns such as Si Mahosot and Muang Phai and smaller, surrounding communities. The combination of settlement layout, epigraphy and sculptural remains shows a fluidity of cultural influence and power of Khmer kings in this peripheral region. The boundary between the two kingdoms is perhaps viewed as being a gap in settlement in the central plain of the region, but it shifted to the western part of eastern Thailand around the early 11th century CE. Such fluctuations in territorial boundaries are a common occurrence in the history of other ancient states.

1. Introduction

Research on the structure of kingdoms and states in early Southeast Asia typically focusses on the core zones and has rarely considered the location and political organization along their boundaries. One of the most frameworks used to explain Southeast Asian political organization is the "Mandala" model. A mandala represents an unstable political situation in an obscurely defined geographical area without fixed boundaries with overlapping circles of power and the center of political power or universal authority could be shifted endlessly. In this model, the edge of the Mandala is as important as the center because it shows the capacity of rulers to maintain communication with distant places for expanding their geographical perspectives (Wolters, 1982: 27–28). The Mandala model contributed to the explanation of political structure in terms of "galactic polity" as cosmological, topographical, and politico-economic features (Tambiah, 1985).

The explanation of political boundaries has been approached at a regional scale is embedded within those concepts with different approaches (e.g. Griswold, 1967; Tambiah, 1976; Wales, 1965). Although the relationship between a center and its boundary is recognized politically, it cannot be separated from economic relations. Significantly, the approach can be integrated under the core-periphery model. It suggests that when the center rose, the surrounding area could be affected in spatial terms. The phenomenon of state formation led to the establishment of the centers along with their periphery under politics and economics, with boundaries playing a crucial role in this process. Mandala concepts remain remarkable in explaining the political boundary progression, particularly the territory of early states in Southeast Asia (e.g. Milner, 1977; Pigeaud, 1960; Songkro, 2015; Wolters, 1967, 1974).

Current archaeological data demonstrates that the earliest state formations in mainland Southeast Asia began to appear in the 3rd-6th centuries CE (Miksic and Yian, 2017: 152–154, 160–165). The frontiers between these new polities evolved gradually and are often marked in the archaeological record by differences in settlement patterns and urban forms. Eastern Thailand represents an important case study for examining frontier zones between early states, specifically between the kingdoms of ancient Khmer in northwest Cambodia and Dvāravatī in central Thailand.

Previous archaeological works showed many moated sites as icons of towns in eastern Thailand (e.g. Mollerup, 2012; Sako, 2013; Sulugsanonan, 1987; Supajanya and Vanasin, 1986; Thiemthat and Musigakama, 1971). The landscape characteristics of the ancient communities were constructed and represented by three features: moated sites, temples, and ponds. The key sites include Si Mahosot (Prachinburi province), Phra Rot (Chonburi province), Phaniet (Chanthaburi province), and Muang Phai (Sra Kaeo province) (Fig. 1). The diagnostic

* Corresponding author at: Department of Archaeology, Faculty of Archaeology, Silpakorn University, Phra Nakorn District, Bangkok 10200, Thailand.
E-mail address: pare.ngernkerd@gmail.com (P. Ngernkerd).

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archaeological evidence reveals distinguishing features of the two kingdoms that reflect the cultural, political, and economic transition that relates to the geographic interface. Some demonstrated the hybridity of style, which gradually evolved into the local style. The character of eastern Thailand seems similar to the case study of Northeast Thailand. Murphy (2024) studied the Buddhist landscape in Northeast Thailand as the consideration of the distinct region in its own right by "sema tradition" while many previous scholars viewed the region as a periphery between Dvāravatī culture and the Khmer kingdom. This approach will also be applied in eastern Thailand.

This paper aims to identify the political boundary between two kingdoms in eastern Thailand to understand the mechanisms and influences of political change in the ancient frontier zone between the 7th to 11th centuries CE. This connection can be tested by examining the typology of settlements and the characteristics of material cultures in the region to determine whether Dvāravatī or the ancient Khmer kingdoms exerted greater influences and, more importantly, to understand the nature settlement in this frontier zone. The conceptual framework of political boundaries and frontiers will be integrated with archaeological data to reconstruct the context of political boundaries in eastern Thailand through the use of site hierarchy and the least-cost path models in Geographic Information System.

2. Dvāravatī and Ancient Khmer kingdoms

The controversy between the terms "state" and "kingdom" still prevails. In archaeological discourse, "state" specifically denotes a form of centralized socio-political organization, whereas "kingdom" is conceptualized under the notion of kingship, which precedes the establishment of a kingdom with centralized processes. Kings were not just political rulers but sacred dignitaries as well (e.g. Carneiro, 1970; Oosten, 1996: 220–221; Wright, 1977). In this paper, both terms "state" and "kingdom" will be used interchangeably to denote forms of political organization, with particular emphasis on "kingdom" to describe the constitutional monarchies in Dvāravatī and the Ancient Khmer polities, as evidenced by historical records.

Dvāravatī and Ancient Khmer emerged as the kingdoms in mainland Southeast Asia around the 7th century CE. The word "Dvāravatī" first appeared on silver coins discovered predominantly in the central plain of Thailand. Some inscriptions reference the kingship of Dvāravatī, with one example found in the transitional zone between central and northeast Thailand (Wimolkasem, 1999). Moreover, sculptures and architectures observed in central Thailand are considered to belong to the Dvāravatī Art due to the distinct corporate styles, especially Buddhist sculptures (such as The Buddha Image on Demons - *Vanaspati*) and

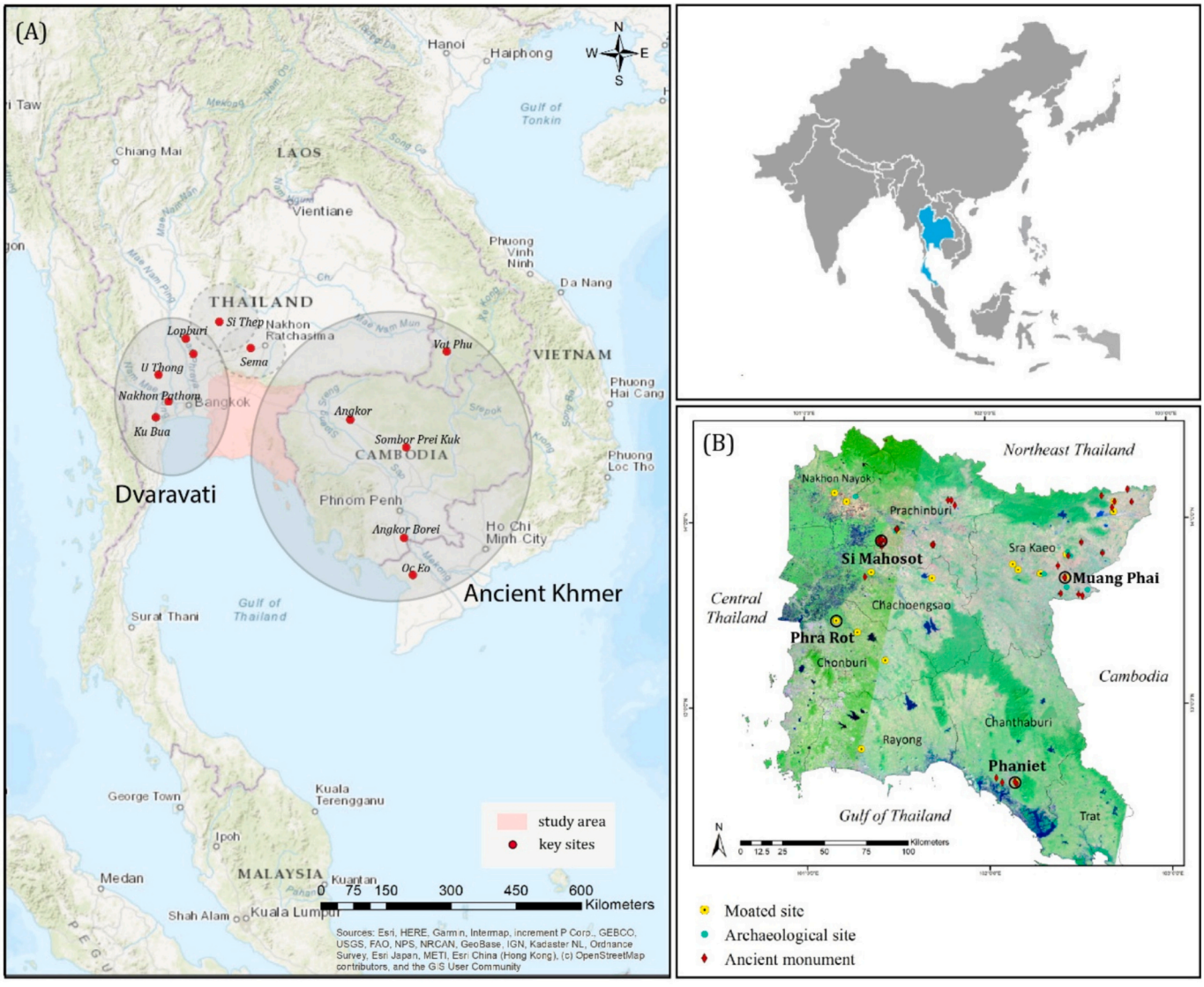

Fig. 1. A map showing (A) the core zone of Dvaravati and Ancient Khmer kingdoms during the 7th–10th century CE and (B) Eastern Thailand as the study area illustrated by archaeological sites.

Dharma wheels (– *Dharmacakra*) showing the distinct aesthetic of Dvāravatī culture. The evidence indicated that Dvāravatī was possibly a kingdom that emerged gradually since at least the 7th century CE.

The political structure of Dvāravatī is unclear and a true capital has yet to be identified. Many scholars believe that it is likely located in central Thailand, potentially at the moated sites such as Nakhon Pathom, U Thong, or Lopburi (e.g. Indrawooth, 1999; Khunsong, 2010; Mudar, 1999; Wales, 1969) based on the presence of large monumental architecture and epigraphic data within the plain of central and western Thailand. The study of settlement patterns and geographical factors reveals that the moated sites, positioned along the paleo Gulf of Thailand functioned as prominent agricultural catchment areas, facilitated access to maritime trade routes and inland waterways. The state development can be derived from these trade connections and agricultural resources (Hutangkura, 2014; Mudar, 1999). The density of sites indicates that this area was the core of the Dvāravatī kingdom (Fig. 1), which persisted until early 11th century CE conquest of Lavapura (Loppuri province) by the Angkorian Khmer king Suryavarman I (Wongsathit et al., 2020).

Many scholars have referred to the Dvāravatī kingdom as a Buddhist State due to the prominence of Buddhist evidence significantly found in the core zone of the kingdom in central Thailand (e.g. Brown, 1996; Fine Arts Department, 2009; Indrawoorth, 2004; Wales, 1969). However, claiming the Dvāravatī kingdom a unified Buddhist state may not be entirely accurate. In fact, Buddhist sculptures and temples have been found across towns of early Southeast Asia since at least the 6th century CE (e.g. Miksic and Yian, 2017; Khai, 2003). Furthermore, evidence of Brahmanism or Hinduism can also be found in those ancient towns, especially Vaishnavism, from the late 6th to the early 7th centuries CE.

These contexts indicated that Dvāravatī emerged gradually and became a kingdom by at least the 7th century CE. The predominance of Buddhism in the Dvāravatī kingdom is viewed as a broader historical process which saw the religion also take root in Srīvijaya (Indonesia) during the 8th – 10th centuries CE (e.g. Indrawooth, 1999; Miksic and Yian, 2017; Woodward, 2005). Today, the primary evidence of Dvāravatī culture is linked to the remains of Buddhist materiality.

The Ancient Khmer kingdom of Funan began in the early 1st millennium CE and began a series of political transformations that would continue to grow throughout the early Modern period. The early extent of Funan covered all of present-day Cambodia, southern Laos, and southern Vietnam by the 6th century CE and was perhaps the most powerful kingdom in mainland Southeast Asia (Vickery, 1998). The demise of Funan influenced the urbanization of subsequent polities, and specifically "Chenla"—the Chinese name of the Pre-Angkor kingdom before the 9th century CE. Based on the epigraphy and architectural evidence, the core zones of Chenla are associated with the urbanized, moated sites of Isānapura associated today with the site of Sambor Prei Kuk in Kompong Thom province, and Srēsthapura, next to the famous temple of Vat Phou in Champasak, southern Laos (Briggs, 1999). The Chenla kingdoms emerged in the late 6th century CE and continued until the 9th century CE with the political consolidation around Angkor on the northern edges of the Tonle Sap lake in central Cambodia (Heng, 2016) (Fig. 1).

3. Political boundary as mandala

Identifying the boundaries political entities in the past is typically complicated by the lack of distinct physical markers in the landscape. The concept of a geopolitical Mandala appeared first in Kautilya's *Arthashasta* of Ancient India as a framework to recognize the spatial relationship between friendly and enemy states from the perspective of a certain kingdom (Shamasastry, 2021). The Mandala model was adopted by Wolters (1982) to examine the concept of a segmentary state, and has been extremely influential to many scholars in Southeast Asia (e.g. Christie, 1995; Chutintaranond, 1990; Dellios, 2019; Murphy, 2024; Vallibhotama, 2015). Unlike other forms of structured organization, this model is used for political situations and administrative systems of unstable kingdoms where fixed boundaries cannot be identified and the power center is fluid (Mabbett, 1978; Murphy, 2024; Talbot, 1994; Vallibhotama, 2015). The Mandala model is commonly depicted as a series of overlapping circles with the central "circle of kings" composed of a center (a core) surrounded by nodes. A king, often believed to be divine in nature, was seen to be the anchor point in these systems and ruled based on a "universal" title of sovereignty known as *chakravatin* (the king of the universe). The spatial model can be seen in the example illustration by Tambiah (1985) in terms of the "galactic polity" based on the Mandala model of Ayutthaya's polity in the 15th–16th centuries CE (Fig. 2). Within this framework, the centers of power, whether large or small, could be arranged in concentric circles, with organizational nodes at various levels being repeatedly replicated throughout the circle. Thus, they were called the overlapping kings (Tambiah, 2013: 511–514).

Tambiah (1985) differs from Wolters (1982) as it also incorporates economic networks to reconstruct the relationships with the system. The galactic polity also reflects cosmological and topographical aspects of space in terms of temple or sanctuary layout, which represent cosmological models on earth as in architectural form as— see at Borobudur, Angkor Wat, or Wat Mahathat.

However, the Mandala model Tambiah (1985) proposed is different from Wolters (1982) in that Tambiah incorporates economic relations to reconstruct the relations among Mandalas. Additionally, the Mandala-based galactic polity also reflects cosmological and topographical aspects of space in terms of temples or sanctuaries layout, which represent cosmological models on earth as seen in architecture—such as Borobudur, Angkor Wat, or Wat Mahathat—from traditional kingdoms of Southeast Asia.

The political process of the Mandala system operates in various ways to maintain the power of kings. In practice, the overlords had to compete with rivals, assert territorial claims, bring others under their influence, and integrate them into the network of loyalties—even those distant from the central core. The political relations between Mandalas were managed through marriage alliances, temple construction, dispute resolution, royal interest collection, and demonstrating the magnificence of the royal capital (Wolters, 1982: 28–30). Such practices appeared in the archaeological record throughout most early kingdoms in Southeast Asia. Warfare, though considered an irregular activity and markedly less visible today, also served as a basis for generating elite heroism and reinforcing authority of the king (e.g. Boisselier, 1966; Briggs, 1999; Vickery, 1998; Wimolkasem, 1999).

The presence of several different Mandalas at the same time presents an important question about how the fringes or borders operate in relation to the different political centers. While borderlines cannot be defined due to political instability, it is worthwhile investigating the borderland or frontiers that exist between them. To identify the structure of political organization inside these zones, it is useful to recognize that the political units within them differ in size and create an internal hierarchy around these central points. The focus of competition between centers will take place on the margins and the nature of the political boundary will be shaped by the degree of interaction between the core of Mandala and its fringe zone (Tambiah, 2013: 511).

The political structure of early Southeast Asia states is characterized by historical records together with material cultures, showing various cultural influences that infiltrated political implications, possibly under the dominance of powerful states during each period. They could be distinguished as loosely centralized states lacking long-term political stability (Junker, 1999: 59–60). Thus, it tended to create highly decentralized states constructed on shifting alliance networks. Mandala or galactic models could be applied to better understand the phenomenon of political structure under the approach of cosmology, geography, and political economy. Although each state had different strategies of centralization and expansion, they were shaped mainly by the concept of the universal king based on the selected ritual of the ruler.

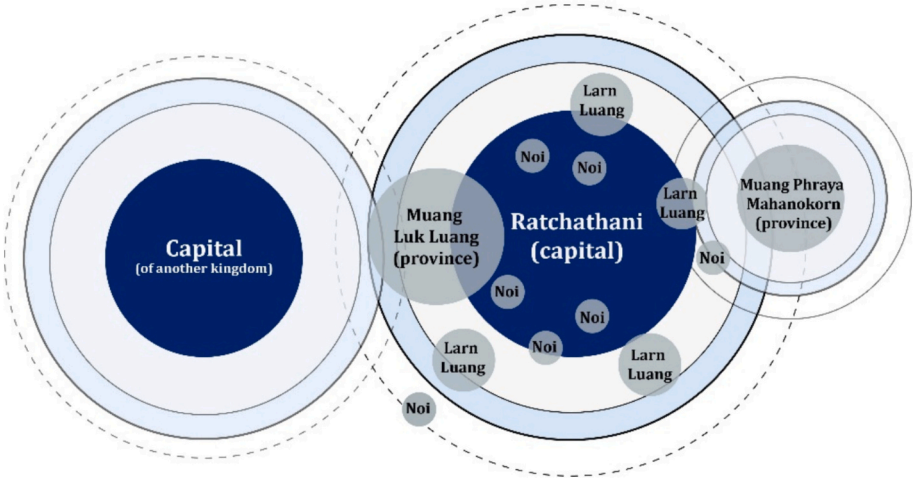

Fig. 2. Model of the political structure of Ayutthaya Kingdom based on the Mandala model (Modified from Tambiah (1985). The Galactic Polity in Southeast Asia. In Culture, Thought, and Social Action (pp. 252–286). Harvard University Press).

4. Conceptualizing boundary and frontier approaches

Peripheral zones in the past have often been studied through terms such as the lens boundary, territory, and frontier and are often linked to colonial impacts on indigenous societies (e.g. Green and Perlman, 1985; Lewis, 2014; Lightfoot and Martinez, 1995; Turner, 1996). Collectively, these terms attempt to show the role of this intermediate zones as important mechanisms for the maintenance of state power, but while the actual differences between them is often overlooked in the literature (e.g. Feuer, 2016; Lewis, 2014). Boundaries are recognized as linear features, while territories and frontiers are zonal. Given that the mandala is a better way to understand Southeast Asian political interactions, emphasis here is given to identifying frontiers, which are defined as zones of hybridity based on cultural exchange or cultural noise, while a border is more related to state authority (Ericson and Meighan, 1984; Lightfoot and Martinez, 1995).

Frontier plays a critical role in negotiation between the centers and peripheries, and is often populated with sites referred to as "frontier towns", "gateways", or "core outposts". These places serve as centers of trade and communication between their parent state and colony or even as a hub of redistribution between the core and periphery. So, these hubs can be recognized as local central places (Algaze, 1993; Casagrande et al., 1964; Vionis and Papantoniou, 2019). However, while frontier towns and core outposts demonstrate the same characteristics, the mode of control over them differs in two ways: a complete direct control as colonial sites of the cosmopolitan frontier and an indirect control that dominates the culture and economy from internal development (Algaze, 1993; Steffen, 1980). As mentioned, it should be noted that one should not claim the peripheral sites as colonies because the peripheral areas can have their own culture adapted from the core culture as a process of localization.

Most archaeological studies of frontiers suggest that "hybridity" is a predominant characteristic for boundary identification (e.g. Dolan and Edwards, 2020; Ericson and Meighan, 1984; Langer and Fernandez-Gotz, 2020; Revire, 2016; Smith, 2003). The hybridization of material cultures among core groups in contact zones provides an opportunity for archaeologists to study the process of frontiers where people created, revised, and modified materials culture in response to different types of contact (Lightfoot and Martinez, 1995: 482). These regions are also distinguished as being remarkably fluid zones. Tensions and dynamics of conflicts, control and coercion are often recorded in these landscapes. The character of a frontier zone is never static and should not be expected (Naum, 2010; Parker, 2006). Defining the actual extent or border of ancient territories is therefore extremely challenging in these zones. The primary clues are the presence of official symbols or features of the political state, such as walls, public buildings, fortifications, and inscriptions, which are placed overtop of the existing settlement and ritual practices of the local population (Trinkhaus, 1984). For example, the capital features a wide variety of official materials, which serve as prestigious goods or gifts through trade and diplomacy. This area is well-organized. In contrast, regional areas or frontiers under the capital's governance primarily display the state's official styles but have lower density, resulting in a sparse distribution. Additionally, the infrastructure, including roads and bridges, forms a transport network that facilitates the movement of goods and people across state territories (Hendrickson, 2010; Sinopoli, 1994: 170–171).

Following Brown (1996), Revire (2016) suggested the presence of an "interface region" discussion between Mon and Khmer polities during the 7th–8th century CE. This theory is based on epigraphical data and sculptures that clearly showed mainland Southeast Asia's religious hybridity (Goodall and Revire, 2021; Revire, 2016: 400–409) and sparks the idea of a frontier zone between the two kingdoms representing the Mon-Khmer polities of Dvāravatī - Chenla.

The concept of the Mandala, with the fringe of overlapping circles, provides an important theoretical framework for understanding the frontier zone in eastern Thailand. The archaeological evidence from this region will be used to illustrate the hybridity of cultural interaction between both official styles and other styles belonging to the locals, along with historical events from inscription data. By doing this investigation, it is possible to identify the cultural fluidity of this frontier region since at least the 7th century CE.

Although the political boundary is still observed to identify the precise borderline, the dynamic nature of the frontier zone is more compelling as a mechanism that helps maintain the stability of surrounding cores through the political Mandala-based processes of the two kingdoms.

5. Evidence from eastern Thailand

Considerable archaeological evidence of ancient moated sites has been discovered in eastern Thailand. These sites are known as "*muang*", or town, are composed of moats and earthen walls in various forms (e.g. Mollerup, 2012; Supajanya and Vanasin, 1986). Previous archaeological research in eastern Thailand suggested that some moated sites, such as Phra Rot, Si Mahosot, and Dong Lakorn, were situated along a paleo-shoreline of the Gulf of Thailand, and had been occupied since at least the 6th century CE (Department of Archaeology, 1986; Lewchaicharn, 2006; Phitsanuphong, 1992; Pilditch, 1992; Sako, 2013; Sulugsananon,

1987). Other moated sites such as Khok Sam Phan further inland were settled since the 3rd -7th centuries CE (Treerayaphiwat, 2017).

The material culture at these sites —including diagnostic pottery and religious materials—appeared after the 7th century CE and was likely in association with the development of rectilinear urban structures. Prestige goods of Chinese and Persian ceramics from the 8th - 9th centuries CE have been found at the moated sites closer to the gulf, particularly Si Mahosot and Phra Rot (Bannanurak, 1991; Phitsanuphong, 1992; Pilditch, 1992; Sulugsananon, 1987). Ornaments made of precious materials—such as gold beads, gold earrings, glass beads, and semi-precious stone beads—can generally be found in eastern Thailand together with local earthenware. Some pieces suggested the relationship in trade exchange networks among the early Southeast Asian states linking coastal and inland settlements.

Eastern Thailand contains several different types of infrastructures that help identify the extent and variety of occupation in the region. Circular or rectangular laterite ponds are the most common and are found across the floodplain in the western part of the region likely in relation to the paleoshoreline. The circular ponds, known locally as Angsila, were dug into laterite layers, and crafting at the rim can be seen in some ponds such as Sra Kaeo, Ban Hoa Sa, and Sra Si Liem. Based on the associated material culture and epigraphic records discovered nearby, these ponds and other earthworks appeared with urban structures during the 7th–11th centuries CE.

Sculpture and architecture attributed to both Dvāravatī and Ancient Khmer cultures are present in the region. The greatest concentrations of religious materials were recovered from the largest moated sites, particularly Si Mahosot, Phra Rot, Phaniet, and Muang Phai. Vaishnavism was remarkable at Si Mahosot, and Woodward (2005) previously suggested that the Vishnu sculptures found here represent a regional school inspired by the peninsular Thai culture. The style of these Vishnu sculptures is also similar to the school of southern Vietnam, and possibly dated to the late 6th to early 7th centuries CE. The artistic influence of Vishnu sculptures from those regions suggests the cultural transition through the networks, and Si Mahosot might have already become established during the early state development of Funan in the 6th century CE. This theory is further supported by other evidence of local trade and long-distance trade, including *kendi* (pottery with a spout), glass beads, gold glass beads, and Roman eye beads (Lewchaicharn, 2005; Stark and Fehrenbach, 2019; Thiemthat and Musigakama, 1971: 14–15).

Numerous Śivaliṅgas, a symbol of Śiva, were also generally found in eastern Thailand archaeological sites. Both Pre-Angkorian (7th – 9th centuries CE) and Angkorian (9th - 12th centuries CE) styles appeared distinctly at sites in Prachinburi and Sra Kaeo provinces, as well as at Phaniet, a moated site in Chanthaburi. The Śivaliṅga signifies that Shaivism might have been adopted as the main religion of ancient Khmer rulers since at least the 7th century CE, as supported by the epigraphy found in the region (Vickery, 1998). The Hinduized religious materials found in this region and generally seen as being the product of interaction with Khmer polities, most notably the Ganesa sculpture from Si Mahosot and the head of Harihara from Phaniet (Briggs, 1999: 51; Diskul, 1973; Khachachiva, 1997; Woodward, 2005: 59–60).

Khmer style temples, referred to as "*prasat*", are widespread in eastern Thailand, especially in Sra Kaeo and Chanthaburi provinces. Lintels of the Pre-Angkorian style dated to the 7th century CE were also discovered. By the 9th century CE, Angkorian temples were constructed following a systematic plan, with the sanctuary surrounded by a moat in the orientation of east-west and flanked on the east by a rectangular reservoir known as a "*trapeang*". Many of these temples were established as new community centers and are not necessarily related or proximal to earlier moated sites. A few examples include the sites of Prasat Khao Lon, Prasat Sdok Kok Thom, and Prasat Khok Ballang (Fig. 3).

Buddhist architecture and sculpture are mostly found in the western part of eastern Thailand, particularly around Si Mahosot and Phra Rot. These sites indicate direct influence of Dvāravatī Buddhist culture between the 8th – 9th centuries CE (Brown, 1996; Revire, 2014). Not only were the sculptures represented in the Dvāravatī style, but some pieces also illustrated the characteristics of the localized style of the local craftsman (Fig. 3).

The establishment of Buddhist temples contributed to a religious landscape that incorporated older moated sites. Significant locations surrounding the moat of Si Mahosot include Phu Khao Thong, Wat Si Mahapho, and the structures in Ban Sra Makeau (Lewchaicharn, 2005, 2006). Similarly, the Buddhist stupa from the late Dvāravatī period was constructed outside the Phra Rot moats, and a group of Buddhist temples are located at the outer moat of Dong Lakorn (Sako, 2013; Sulugsananon, 1987). These locations are renowned as the Buddhist landscape of Dvāravatī in central Thailand, where it is more common for temples to be built outside the moats (Gallon, 2013: 178–179).

Sanskrit inscriptions found throughout the study area provide important data about the state organization of ancient Khmer established in the eastern part of the region during the 7th – 11th centuries CE. The royal orders predominantly reflect the political structure centered on a ruler as the king. By contrast, the Dvāravatī texts in eastern Thailand, show less interest in showing localized political authority and instead focus on the Buddhist content. Each of the Dvaravati inscriptions was discovered in the western part of the region and, based on their languages, letters, and styles, can be dated to the 8th and 9th centuries CE (Revire, 2014: 245, 251) (see Table 1).

Inscriptions from the Angkor period (9th to 15th centuries CE), record the increasing influence of the Khmer in the region. Texts found in Sra Kaeo and Prachinburi provinces includes names of towns such as *Vijaya pattana* (K.1152), *Bhadhara pattana* (K.235), and *Avadhayapura* (K.1053) together with villages or sub-districts with the Khmer prefixes or suffixes of *sruk*, *grama,* and *visaya* (Kaewkhlai, 1986; Majumdar, 1953; Vickery, 1998). Their use indicates that the Angkorian administration was strongly implemented in the local area. Several Angkorian inscriptions, such as K.957, K.233, K.999, and K.1152, revealed that the region of Ta Phraya, the northern part of Sra Kaeo, was directly under Khmer rule. The royal edict of Rajendravarman (941–968), who declared victory over and claimed Ramanya and Champa in K.872 (Cœdès, 1937: 97–104), was discovered in Ta Phraya. Another inscription built by Suryavarman I (K.232 in 1016) was discovered on the door frame of Prasat Khao Lon. Moreover, the Angkorian authority also extended to the southern part of the region at Phaniet during the 9th century CE, based on the inscription K.479 (Veeraprajak and Thasukhon, 1986: 63–67).

The archaeological evidence from eastern Thailand suggests that the region functioned as an interface zone between the Dvāravatī and Ancient Khmer kingdoms. The hybridity of styles in sculpture and architecture is particularly remarkable and indicates shifting levels of control or influence. Prior to the 9th century CE, the Buddhist emphasis suggests a strong association with Dvāravatī from central Thailand. This influence continued until the political expansion under Angkorian kings Rajendravarman and Suryavarman I during the 10th–11th centuries CE. To examine this historical transition, the typology of settlements will be analyzed to assess the influence of both kingdoms and to better understand the nature of the frontier zone.

6. Materials and methods

This study focuses on documenting moated and other archaeological sites of the 7th–11th centuries CE in eastern Thailand. The database of ancient settlements in Thailand created by Supajanya and Vanasin (1986), the Fine Arts Department of Thailand (FAD), and Department of Archaeology, Silpakorn University was used to generate a complete inventory of all archaeological features (e.g. moats, earthworks, canals, ponds, and mounds) within the study region (e.g. Baoneard, 1994; Duangdee and Bhumpongpate, 1977; Lewchaicharn, 2005, 2006; Mollerup, 2012; Moolmongkol, 2011; Phitsanuphong, 1992; Ratanavirakul, 1990; Sako, 2013; Srisuvithanon, 2019; Sulugsananon, 1987). Aerial

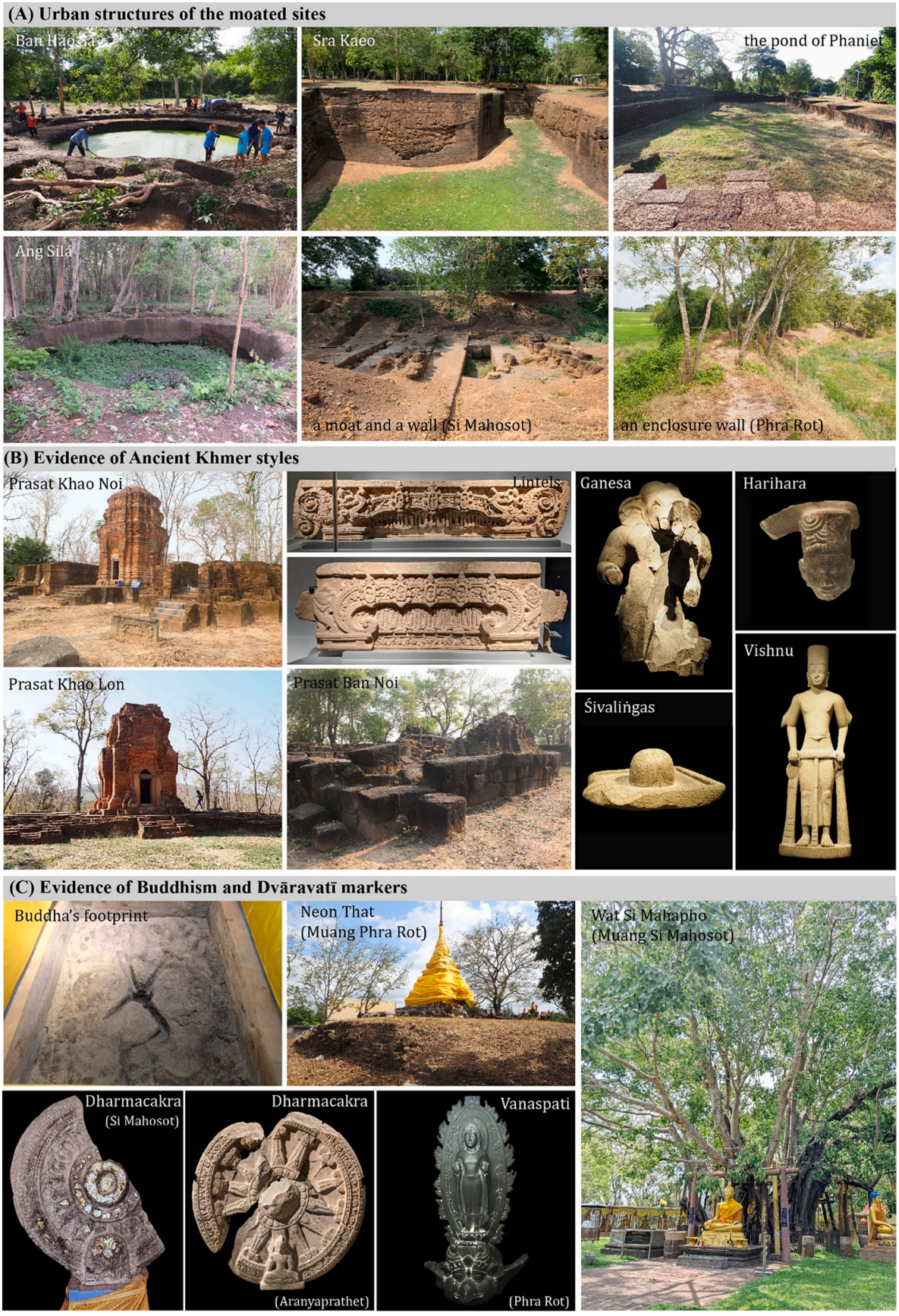

Fig. 3. Examples of diagnostic evidence from eastern Thailand.

Table 1
The important inscriptions found in eastern Thailand showing the difference in description contexts during the 7th – 11th centuries CE.

ID.	Source	Description context	Reign date (CE)	Text date (CE)	References
K.969	Chong Sra Cheang, Sra Kaeo	Royal orders of Mahendravarman	598–616	–	(Vickery, 1998)
K.502	Phaniet, Chanthaburi	Royal orders of Isanavarman I	616–637	–	(Cœdès, 1924: 345–358; Kaewkhlai, 1998)
K.503	Phaniet, Chathaburi	Royal orders of Isanavarman I and showing the name *"Candhra- (pura)"*	616–637	–	(Cœdès, 1924: 345–358; Kaewkhlai, 1998)
K.506	Khao Noi, Sra Kaeo	Royal orders of Bhavavarman II		637	(Jacques, 1986: 80–82; Vickery, 1998: 338)
K.505	Khao Rang, Sra Kaeo	Royal orders of Bhavavarman II		639	(Cœdès, 1953: 23–24)
K.1150	Prasat Kud Tare, Sra Kaeo	Royal orders of Bhavavarman II which also reveals *"Jyesthapura"*, a town in his vicinity and *"Sambhuka"*, a polity which relate to the Dvāravatī kingdom	637–650	–	(Jacques, 1986: 80–82; Vickery, 1998: 338) and (Amatayakul, 1973: 64–70; Khunsong, 2014: 191–192).
DW.38	Wat Mon Nang, Chonburi	A votive tablet of Buddhism (in Old Mon language)		–	(Bauer, 1991: 63)
–	Dong Lakorn, Nakhon Nayok	Ye Dhamma – the Buddhist content (Pali language)		–	(Sako, 2013: 343)
K. 957	Ban Phang Phuay, Sra Kaeo	Royal orders of Rajendravarman		941	(Cœdès, 1964: 137–140)
K.232	Prasat Khao Lon, Sra Kaeo	Royal orders of Suryavarman I		1016	(Cœdès, 1954: 228–233)
K.235	Prasat Sdok Kok Thom, Sra Kaeo	The royal history after the declaration of Jayavarman II. This epigraphy was built in the reign of Udayadityavarman II		1052	(Kaewkhlai, 1986: 181–227; Majumdar, 1953: 368)
K.997	Prasat Sra Morakot, Prachinburi	the Buddhist content (in Old Khmer and Pali languages)		1061	(Songkro, 2015)

photos and satellite imagery were obtained and then employed to interpret the layout of moated sites and surrounding features in relation to geomorphology. The aerial photos from the Royal Thai Survey Department (RTSD), including the WWS project in 1952, the VAP-61 project in 1968, and the NS3 project in 1971, were analyzed using a Topcon mirror stereoscope. Interpretation of these images was enhanced by the addition of various satellite imagery including LANDSAT 8 from the United States Geological Survey (USGS) and a collection of high-resolution imagery sourced from Google Earth through a geographic information system (GIS) environment software. Finally, a high-precision Digital Elevation Model (DEM), supported by the TanDEM-X project (TerraSAR-X add-on for Digital Elevation Measurement), was used for modelling the least cost path analysis between the sites.

The collected datasets were assembled in digital form using GIS software, incorporating digitization and background topographic data relating to hydrology, land use, and elevation derived from the 1:50,000 scale topographic mapping data for Thailand (RTSD). The preliminary interpretative maps were loaded into handheld GPS units, and all newly identified features were systematically investigated by the ground surveys conducted from 2021 to 2023. The comprehensive landscape records of archaeological sites were then completed in 2023.

The process of modelling potential transportation connections as the least-cost path analysis is stimulated by integrating archaeological evidence—including inscription data, moated sites, mound sites, temples, and ponds—with the DEM into the GIS software. Criteria regarding site location and form are required to calculate the site density, which should help indicate the cluster of ancient communities in the study area. Site hierarchy is also taken into account based on on-site location and size to identify the urban center in the region. The results from the GIS were integrated with archaeological data to understand the association of moated sites within the concept of state development related to the core of Dvāravatī and Ancient Khmer kingdoms. This involved comparing the features of moated sites throughout eastern Thailand to determine whether they share more similarities with the Dvāravatī or the Khmer typologies.

A few limitations must be mentioned in relation to the collected datasets. First, although the remote sensing method can highlight cultural features imprinted on the surface, some archaeological sites or features have recently been disturbed or physically damaged. Second, if the diagnostic artifacts were absent pedestrian surveys, determining the age of was reliant on morphological associations of moats, rice fields, ponds, and certain earthwork features. In future work, archaeological excavation should be considered the fundamental methodology for reconstructing land use, especially moated sites that contribute to the research of the relationship between urban forms and their cultural transitions in each period.

7. Central place of networks and transportation

The GIS results suggest that the ancient community structures in eastern Thailand can be defined by the presence of two to three types of features: moated sites, temples, and ponds. Fifteen moated sites of various sizes and shapes were found in the study area that represent a variety of different urban forms. The differences in size and shape are used to infer the presence of settlement hierarchies and potential assessing network connections within the region. Central place analysis was applied to examine the site hierarchy and explore the relationship between the moated sites and their networks (Christaller, 1966; Vionis and Papantoniou, 2019). Least cost path (LCP) was employed to model overland connectivity between the central places to illustrate transportation routes in ancient times and highlight the relationships between site location and the density of the routes (e.g. Dolan and Edwards, 2020; Khamsiri et al., 2023).

7.1. Site hierarchy: Central town, town, and village

Site hierarchy analysis indicated three classifications of moated sites based on size and shape with a hypothetical boundary of the central town (Fig. 4). The first group or "central town" covers approximately 1.0–2.4 sq.km, typically rectangular or rounded-corner rectangular shape. The second group, referred to as "town", covers an area ranging from 0.5 to 1.0 sq.km. It is generally characterized by a circular shape, although it features irregular extensions that suggest different phases of moat construction and possibly variations in land usage. The third and smallest group associated with a "village", has an area of 0.08–0.5 sq. km, typically in a circle or rounded-corner square shapes generally located 10–40 km surrounding a central town and a town (see Table 2 and Fig. 4). It is interesting to note that the structure of villages here is

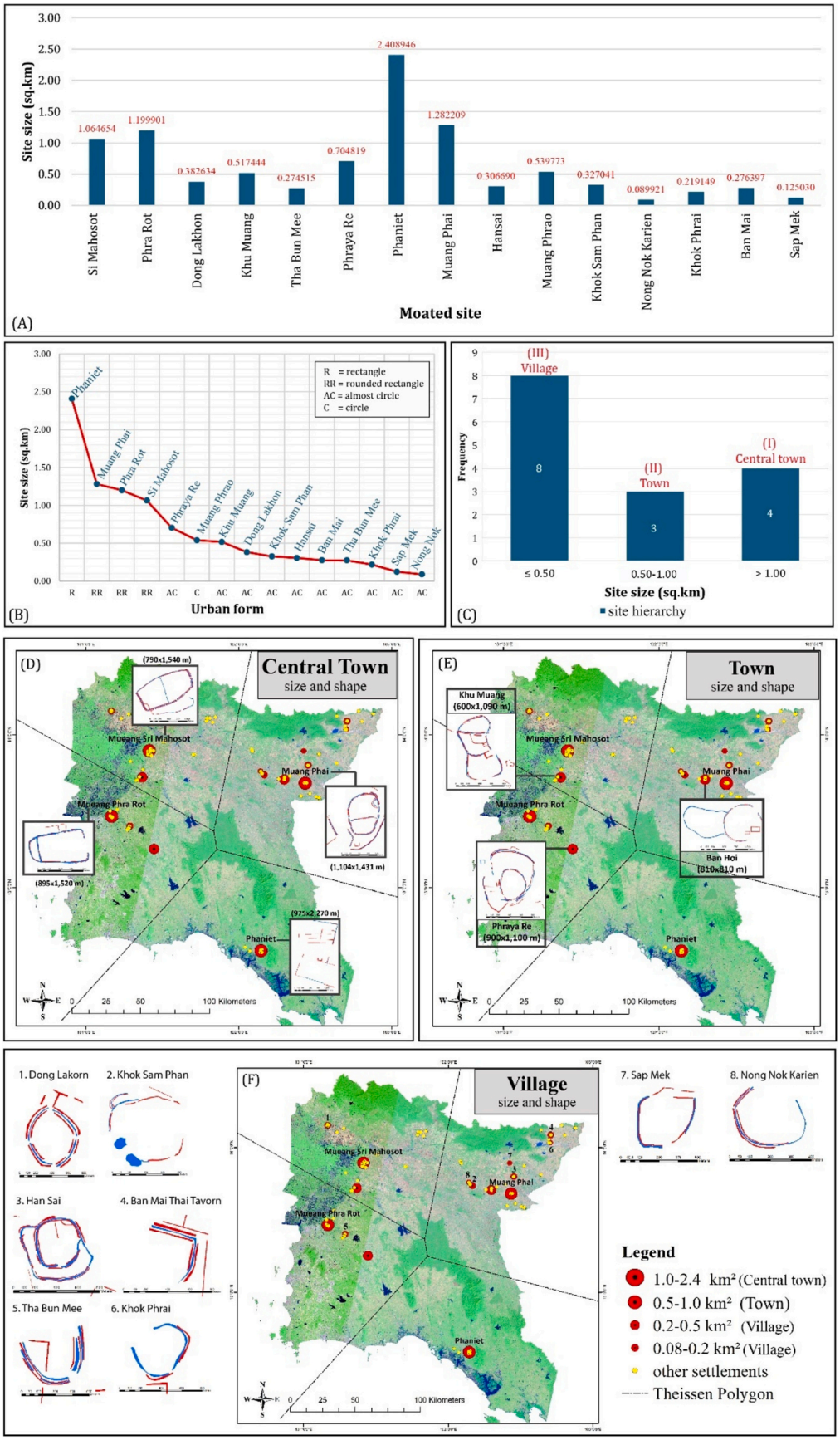

Fig. 4. The distribution of site size. (A) – (C) indicates the relationship between its size and urban form. It suggests that the site hierarchy should be classified into three rankings as follows: (D) Central town, (E) Town, and (F) Village. They are significantly different in shapes, which implied an urban form, while the Theissen polygon represents the hypothetical boundary of four central towns.

Table 2
Site hierarchy of moated sites in eastern Thailand based on size and shape.

Hierarchy	Moated site (7th–11th centuries CE)	Size (km^2)	Urban form	Key moated sites in Southeast Asia during the 1st millennium CE (the similarity of urban form)
1 Central town	Si Mahosot	1.06	Rounded rectangle	Central Thailand Nakhon Pathom, Ku Bua, and U Thong Myanmar Beikthano and Halin Mekong Delta Sombor Prei Kuk, Oc Eo, and Vat Phu
	Phra Rot	1.19		
	Muang Phai	1.28		
	Phaniet	2.41	Rectangle	
2 Town	Khu Muang	0.52	Almost circle with expanded irregular shape	Central Thailand Si Thep, Muang Bon, and Lopburi
	Phraya Re	0.70		
	Muang Phrao	0.54	Circle with expanded irregular shape	Northeast Thailand Sema, Fa Daed Song Yang
3 Village	Dong Lakorn	0.38	Almost circle	Central Thailand Inner moated site of Muang Bon, Chansen, Khu Muang, and U—Ta pao
	Khok Sam Phan	0.33		
	Ban Mai Thai	0.28		
	Thavorn			
	The Bun Mee	0.27		
	Khok Phrai	0.22		
	Sap Mek	0.13		
	Nong Nok Karien	0.09		
	Han Sai	0.31	Almost circle with expanded rounded corner square	

still slightly different from those of northeast Thailand moated sites which consist of multiple moats, in contrast to the presence of a single moat and rampart observed here (Boyd et al., 1999a, 1999b; Moore, 1988).

Table 2 and Fig. 4 show the transition in settlement form from the earlier prehistoric form to those that begin to integrate the Indic influences. The main towns in the early historic period are typically rectilinear in shape, with those featuring square corners being more likely associated with Indic level planning. The latter settlements follow the systematic rectilinear plan that notably appeared in the ancient Khmer kingdom by the at least the late 6th century CE. In contrast to other Southeast Asian kingdoms during the first millennium CE—such as Angkor Borei (Funan, Vietnam), Halin (Pyu, Myanmar), and Nakhon Pathom (Dvāravatī, Thailand)—the main towns tended to have the rounded-corner rectangular and irregular forms (Fig. 5).

The urban form can also symbolize a site function or its status since the rectangular or rounded-corner rectangle tends to be particularly associated with main towns, signifying its importance. This pattern was also evident in four central towns identified in the study area.

Central towns contain a higher density of religious buildings relative to other sites identified in this survey and are considered to be the community anchors within a given region (Fig. 6). Lower-ranking settlements such as towns and villages are associated with moated site form typically found across late prehistoric and early historic Southeast Asia.

The density of structures and prestige goods in the central towns indicate that it was likely occupied by an elite, ruling class, while the surrounding towns and villages were occupied by commoners, most often outside the moated areas. The inner area of most central towns is dominated by temple structures (e.g., Building no. 22, 25, 86 in Si Mahosot, Prasat Muang Phai in Muang Phai, Neon That in Phra Rot and Prasat Phaniet in Phaniet). The diagnostic materials found in the center zone, including religious sculptures, Chinese ceramics, Persian ceramics, *kundi*, and glass beads, also suggest control of trade and exchange.

7.2. Least Cost Path Analysis (LCP)

The potential overland routes between the central towns were generated using the least cost path (LCP) modelling analysis. Each of the four central towns—Si Mahosot, Phra Rot, Phaniet, and Muang Phai—was used as starting and destination points to identify intersections with other towns and villages in the landscape. The results show four groups of overland routes associated with each central town (Fig. 6).

Identification of past transportation routes relies on correlating the physical relationship between site locations and cultural landscape features (e.g. Dolan and Edwards, 2020; Khamsiri et al., 2023). Based on the LCP model, several different routes run across the high-elevation mountain and the plain; however, a few of them do not intersect with any documented archaeological sites. For example, six routes to other towns from Phaniet were generated, yet archaeological features have been rarely discovered along the mountainous route to Si Mahosot in the western part of the region. Hence, such routes were not likely to be transportation routes in the early historical period. Three other routes connected the ancient towns across the western and eastern parts of the central flat plain of eastern Thailand. These routes often intersected with ancient communities and also showed some overlap with modern highways.

The analysis of site hierarchy and LCP reveals the presence of different networks between the central town and other settlements in eastern Thailand. The concentration of sites estimated by the kernel density tool highlights the significant concentration at Si Mahosot, which gradually decreases along the paleoshoreline before increasing again at Phra Rot, thus identifying both towns as a central town. Moreover, the alignment of water storage facilities and monuments featuring consistent architectural styles along the LCP route suggests that this route functioned as an essential transportation corridor connecting these ancient towns. In the inland, the density is relatively lower in the central part of the region and increases progressively around the Muang Phai zone. This gap potentially delineates the boundary between Si Mahosot and Muang Phai. In contrast to Phaniet at Chanthaburi, the evidence only clusters around their own urban center, signifying that the towns functioned as isolated centers in the southern part of the region.

The spatial distribution of archaeological features reveals the remarkable concentration of temples and ponds dated from the 7th – 11th centuries CE at the four central towns, particularly in the four central towns, with Si Mahosot being a primary focal point. The rectilinear forms dating to the early 7th century CE indicate the urbanism of four central towns, each functioning as the central place of each peripheral zone. The examination of transportation networks, through methodologies including LCP analysis and geographical data assessment, provides insights into the intricate political, economic, and cultural transitions during this period. This understanding emphasizes the importance of regional connectivity in shaping the dynamics of urban development and influence across the central towns.

8. Discussion

Both the Dvāravatī and Khmer kingdom sought to expand their territory to establish the universal center under Mandala geopolitical concept. The core zone of these states frequently shifted and in turn we see changes in their frontiers. Eastern Thailand, a peripheral zone for both states, is characterized by a distinct cultural hybridity, indicating that control was sought and achieved at different times.

The integration of site hierarchy, LCP analysis, and archaeological evidence suggest that the cultural network of eastern Thailand was

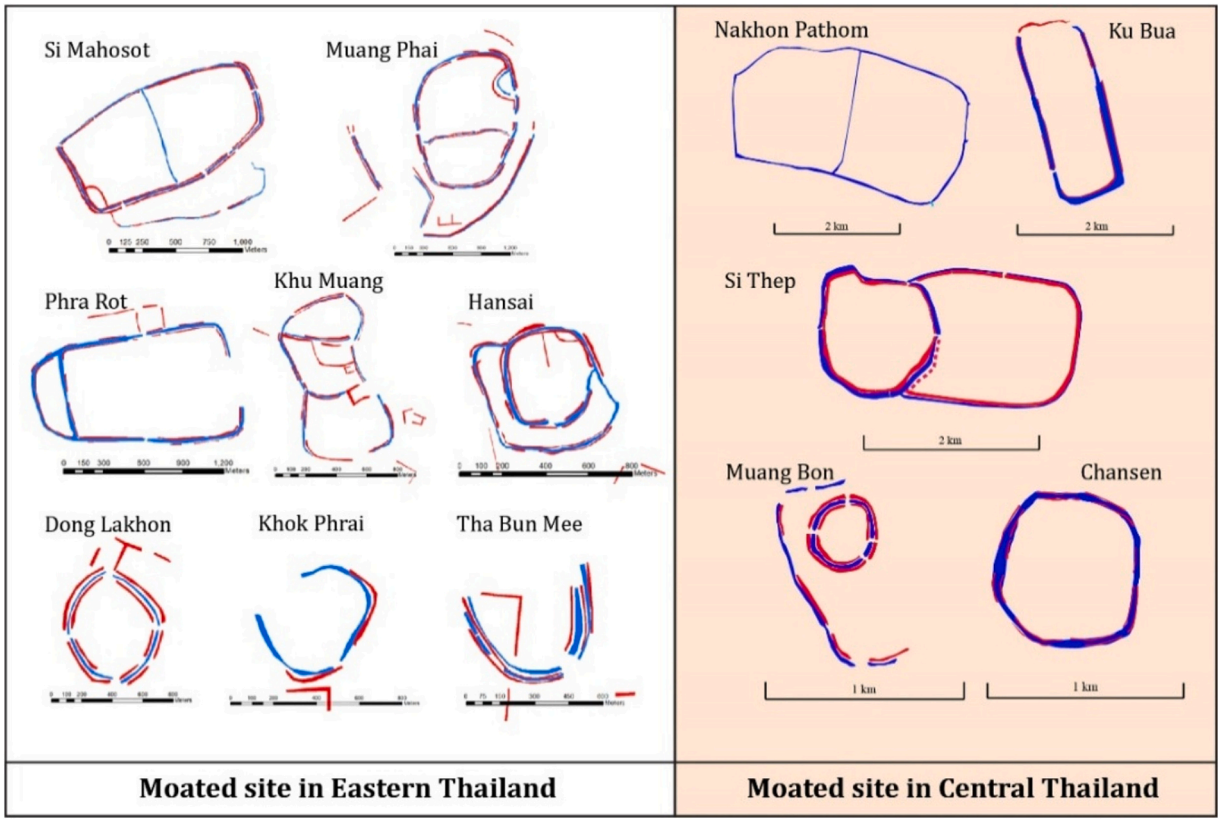

Fig. 5. Comparative urban forms between the example of moated sites in eastern Thailand and central Thailand before the 12th century CE.

divided into two parts – the western and eastern parts of the region. The alignment of moated sites and communities along the western floodplain (border of the paleoshoreline) indicates the local cultural network, as evidenced by their characters, contexts, and landscapes, particularly by the presence of the circular or square laterite ponds located in a range of 5–15 km between communities. The markers of Dvāravatī Buddhism, such as *Dharmachakra* and *Vanaspati*, appeared in eastern Thailand during the 8th–9th centuries CE, together with stupas and Buddhist monuments surrounding the moats. This pattern represents the Buddhist cultural landscape of Dvāravatī towns in the western part (Gallon, 2013; Revire, 2016: 399–400). However, the presence of the Buddha's footprint and a sculpture of Buddha in meditation (of the Funan style) at Si Mahosot, along with the trace of Visnu sculptures prevalent before the cultural expansion of Dvāravatī to eastern Thailand, suggest that the western part of the region might have developed as a state contemporaneously with others in mainland Southeast Asia, around the 5th–7th centuries CE, with Indic religious incorporation and became a buffer state between Dvāravatī and Ancient Khmer kingdoms during the 7th – 9th centuries CE, according to religious materials and architectural styles that they represent both the hybridity and a unique expression of eastern Thailand such as the circular and square laterite ponds, sculptures of Buddha with stupas, and the Ganesa sculpture. This duration is related with the sema tradition of Northeast Thailand as a state or one Mandala (Murphy, 2024), so it is plausible that the western part of Eastern Thailand could potentially develop their own distinct cultures and attempt to empower neighboring areas through their cultural development in the same way of Dvāravatī and the Khmer.

For the eastern part of the region, epigraphical data and religious materials since the 7th century CE show the prevalence of Shivaism connected to the expansion of the Khmer kingdom. Pre-Angkorian and later Angkorian styles, represented by temples and reservoirs (*Trapeang*), were predominantly found in sites located in present-day Prachinburi and Sra Kaeo provinces, as well as Phaniet in Chanthaburi. The influence of Pre-Angkorian culture in this zone was widespread not only materially but also in terms of politically through the numerous texts found there. According to inscriptions K.1150 and K.506, Muang Phai and Phaniet were within the vicinity of the Khmer kingdom since at least the 7th century CE, and were directly referred to as *Jyesthapura* and *Candhrapura*.

Furthermore, evidence of warfare between Dvāravatī and Chenla kingdom during the reign of Bhavavarman II is indicated through a reference at the site of *Sambhuka*, an ancient town in central Thailand associated with the Dvāravatī kingdom during the 7th–8th centuries CE. These references were inscribed on K. 1150, K.577 and the epigraphy of Prasat Preah Khan at Angkor (Amatayakul, 1973; Boeles, 1967; Khunsong, 2010). The mention of the town in inscriptions implies the relationship between the rulers of Dvāravatī at Lopburi and Nakhon Pathom that it also found in eastern Thailand from K.1150, so the town can represent to be Dvāravatī kingdom from central Thailand that they conflicted with the Chenla kingdom during that time.

The instability of Chenla in the late 7th century CE led to the expansion of Dvāravatī into eastern Thailand, which at the time was under the authorization of Bhavavarman II of Chenla (637–650), as evidenced by inscriptions K. 506, K.507, and K.1150. Some Dvāravatī markers, such as *Dharmachakra* and Buddhist sculpture, have also been found at Aranyaprathet in Sra Kaeo province on the modern day border with Cambodia (Brown, 1996: 131). Additionally, the inscriptions related to Buddhism and the Mon language of this period were discovered in the western part of the region, indicating cultural exchange until the middle of the 8th century CE.

The distribution of systematic plans of Angkorian temples became increasingly widespread across eastern Thailand by the 10th century. Numerous inscriptions further illustrate the political expansion of Angkorian to its periphery, especially between the reign of Rajendravarman and Suryavarman I. These features demonstrate that the Angkorian culture covers not only the landscape features including

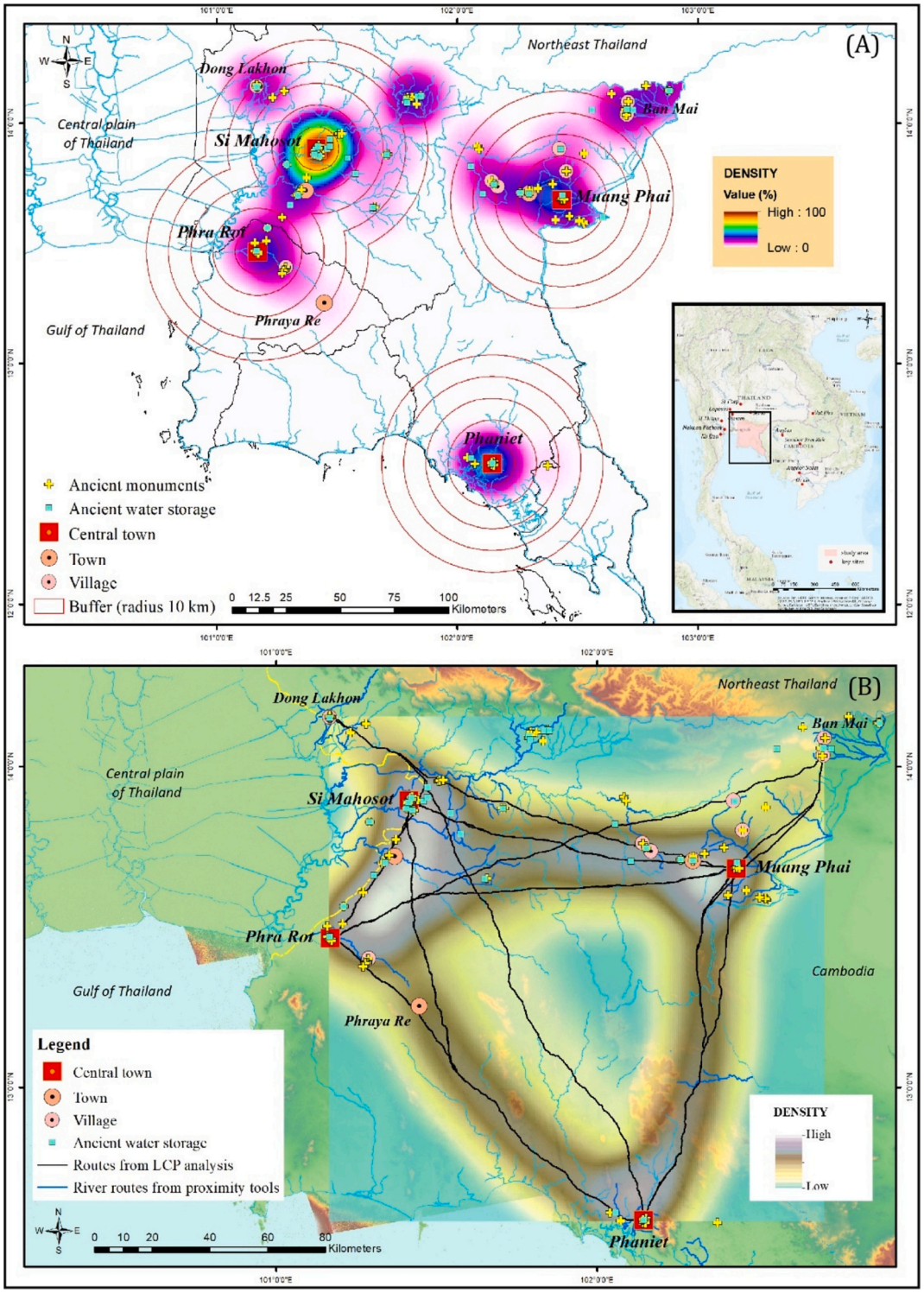

Fig. 6. Map of site density in eastern Thailand showing: (A) the hotspots of the four central town moated sites, with the highest density at Si Mahosot. The 10-km buffer of each town illustrates the spatial between those moated sites and ancient communities, which implies that the site locations might related to the distance between each central town and (B) LCP analysis across topographic elevation map between the central towns in the eastern Thailand by GIS software.

urban forms, rice fields, and ponds in eastern Thailand but also its political power was presented in terms of the land donations, the temple's establishment, and the tax collection which they appeared in epigraphical data.

The power of Angkor is further reflected in the inscription K.410 of Suryavarman I found at Lopburi (known as *Lavapura*) of central Thailand. This suggests that the Dvāravatī kingdom in gradually declined during the reign of Rajendravarman and its lands were eventually occupied by Angkor in the reign of Suryavarman I (Wongsathit et al., 2020: 136–143). The western zone of eastern Thailand, which previously functioned as a buffer state between Dvāravatī and the Ancient Khmer kingdom, came under the Angkorian authority in the second half of the 10th century CE (Fig. 7).

The Mandala model and frontier approach offer a useful way of

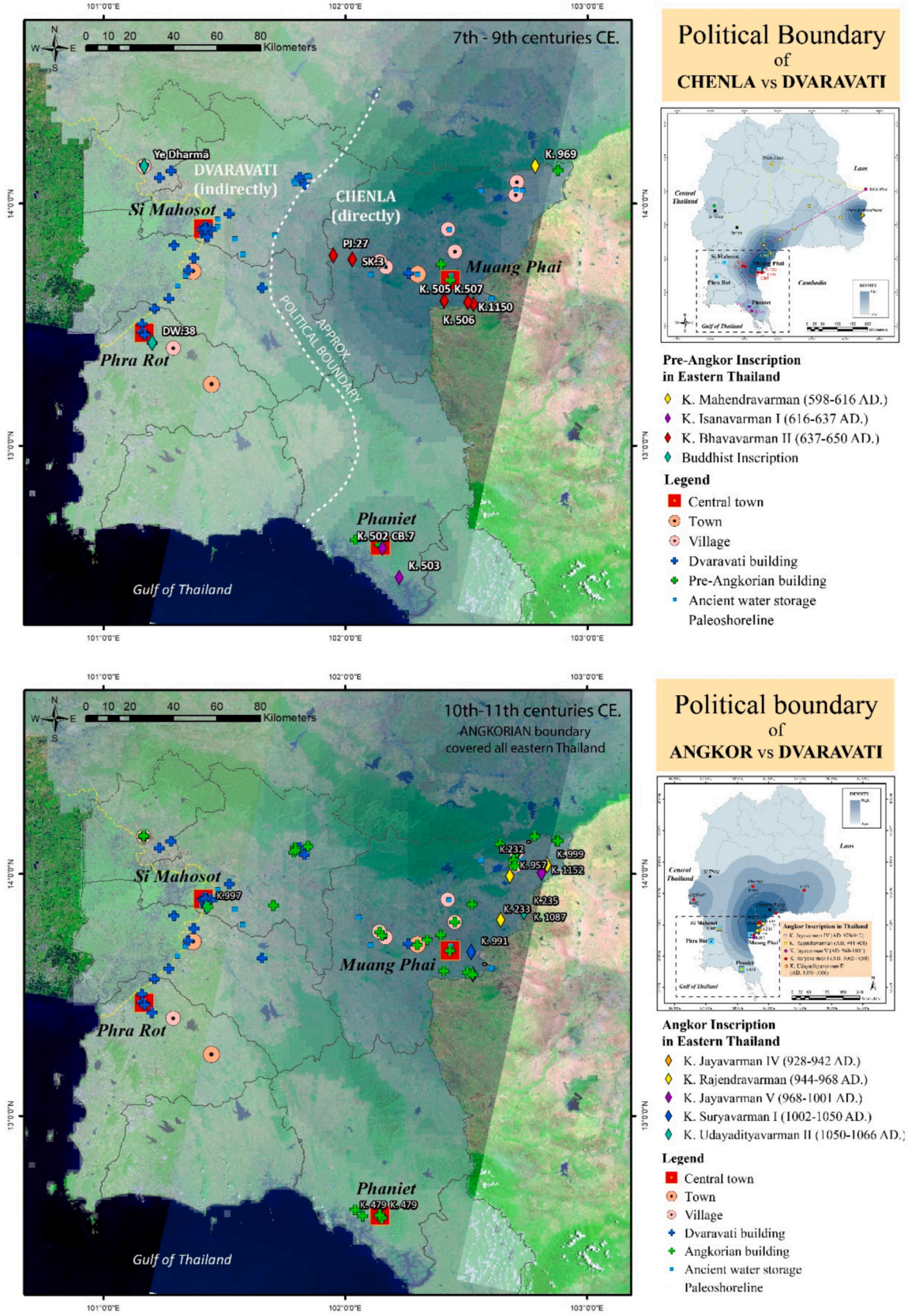

Fig. 7. A map of eastern Thailand showing the political boundary between the Dvaravati and Ancient Khmer kingdoms before the 11th century CE.

understanding the interaction of the groups occupying the space between Dvāravatī and Ancient Khmer, in eastern Thailand. Urban forms in this area are associated with administrative functions within the respective kingdoms. Both rounded-rectangular and circular sites of Dvāravatī and Ancient Khmer in eastern Thailand are observed.

The character of some moated sites in eastern Thailand is comparable to the Dvāravatī examples in central Thailand—Nakhon Pathom, Ku Bua, Si Thep, Chansen, and Muang Bon (Fig. 5). Mudar previously argued that the administration of Dvāravatī could be classified into four levels based on the settlement size (Mudar, 1999). The result of the site hierarchy analysis in this study demonstrates that the four central towns, each of rectangular form, likely served as the regional center in this frontier zone, while the three towns and eight villages served as the district and sub-district center forming a local network. This hypothesis is supported by the LCP model and the distribution of the villages, which reveals the overland routes connecting the central towns. Some of the routes run through the towns and villages, particularly those in the plain between the western and eastern parts of the region. The key route is the east-west connection between the sites of Si Mahosot and Muang Phai. It appears that Si Mohosot and Phra Rot to the south were the most important regional outpost of the Dvāravatī kingdom in the early 8th century CE. Moreover, canals running through the ancient sites in the region may have been another route for transportation between the sites that they served as the alternative connection between overland routes to cut short distances and link the central towns to other communities within the local mandala.

The rectilinear settlement plan associated with Khmer influence can be found at Phaniet (in Chanthaburi province) and some sites in Sra

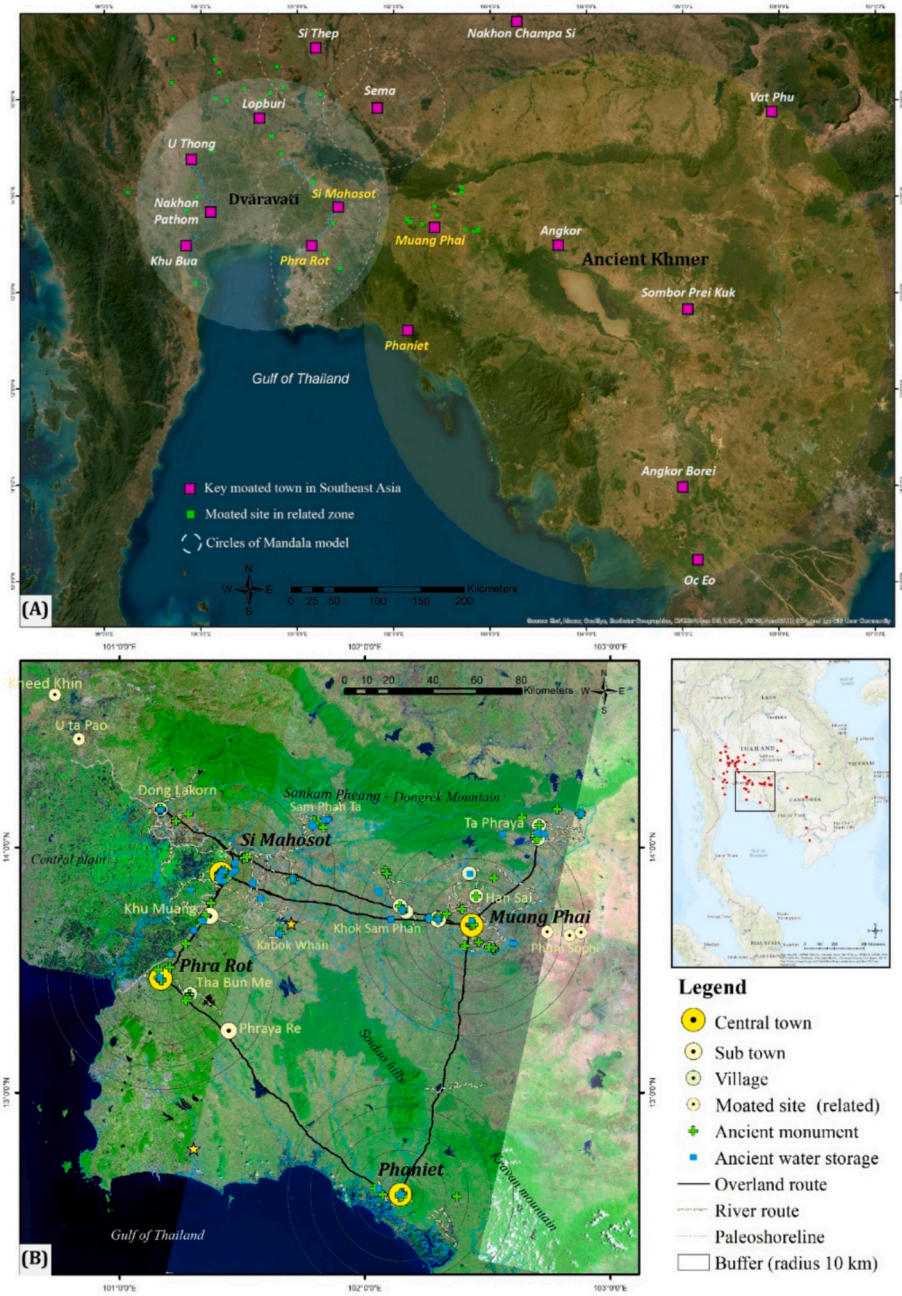

Fig. 8. Implication of political structure in Eastern Thailand based on spatial analysis. (A) The overlapping circles are conceptualized by mandala model between Dvāravatī and Ancient Khmer kingdoms. (B) LCP analysis illustrates both the overland and riverine transportation, which supports that Si Mahosot and Muang Phai should be promoted to frontier towns based on their geopolitical conditions.

Kaeo province. The variation in urban forms suggests that political networks in the region were created systemically by the implication of its location and urban spaces. The inscription data suggests that Khmer power extended into the eastern part of Thailand since at least the 7th century CE with Muang Phai and Phaniet being their primary outposts.

Si Mahosot and Muang Phai later developed into key frontier towns between the two kingdoms. The status of Muang Phai as *Jyesthapura* is further supported by the inscription K.1150 and Dvāravatī style sculptures, including other markers, spread across Si Mahosot rather than reflecting royal orders of Ancient Khmer. Phra Rot seems to have been directly under the rule of Si Mahosot, while Phaniet was perhaps ruled by its own rulers but integrated within the Khmer political system.

These four towns located on the within the shared mandalas of the Dvāravatī and Khmer kingdoms created an important zone for rulers who sought to maintain regional communication and ensure political stability. Si Mahosot and Muang Phai, owing to their location and geopolitical importance, likely acted as gateways or hubs for trade and other interactions between the kingdoms. The geographic significance of these towns is emphasized by their positions at the peripheries of the hypothetical Mandalas of the Dvāravatī and Khmer polities (Fig. 8, upper). This geopolitical relationship is similarly replicated in the mandalas created through the hierarchy and LCP analysis for these two sites (Fig. 8, lower).

The spatial analysis of settlements in eastern Thailand reveals the presence of an important frontier between the two kingdoms of Dvāravatī and the Khmer. The considerable “cultural noise” between sites here serves to link them together generally and shows a fluidity of community and state relationships over time. In contrast to typical conceptions of how territory edges are marked, the “boundary” in this region is perhaps best viewed as being a gap in settlement.

The appearance of the gap in the central plain of eastern Thailand with the condition of the mountain in the south of the plain is a borderline of the two kingdoms after the Dvāravatī from central Thailand empowered and extended into the vicinity of Ancient Khmer polity during the 8th–9th centuries CE. Later, the border shift was subject to the political stability of states of different periods, with the boundary of Angkor moved further into the west of eastern Thailand region in the early 11th century CE during the reign of Suryavarman I. The application of the Mandala geopolitical concept suggests that the two cores, the Dvāravatī and Ancient Khmer, settled Si Mahosot and Muang Phai as a frontier town in the outer circle of Mandala. Their characters reflected the hybridity of culture and ritual, as evidenced through material culture, inscriptions, and urban form, as a regional center in the periphery.

9. Conclusion

Archaeological data from eastern Thailand shows a marked cultural diversity that was shaped by the influence of two of Southeast Asia's most influential states. The cultural noise that characterizes this frontier region emerged during the early phase of state formation in the 7th century CE, following the decline of the Funan state in the Mekong Delta. Moreover, the development of the Maritime Silk Road also likely contributed to the rise of urbanism of the ancient community across eastern Thailand, under the authority of the Dvāravatī of central Thailand and the Ancient Khmer of southern Cambodia and Laos.

The GIS spatial analysis identified the presence of four central towns—Si Mahosot, Phra Rot, Phaniet, and Muang Phai—that anchored the surrounding community. These towns share a similar rectangular form and were ideally positioned in the landscape to provide access into and beyond their proximate state. Si Mahosot and Muang Phai likely functioned as the gateway or the frontier towns between the Dvāravatī and Ancient Khmer from at least the late 8th century CE, acting as a hub for trade and communication between the core and their peripheries due to the strategic location.

The settlement pattern and site density can help identify the political boundary of the two cores, with each Mandala's fringe equal to the state boundary situated in the middle area of the region. The distribution of ancient Khmer inscriptions, along with shifts in sculpture and architecture styles and built landscapes discovered in the moated sites of each period, indicated that the political boundary between the Dvāravatī and Ancient Khmer kingdoms had expanded to the western part of eastern Thailand during the period of Suryavarman I around the early 11th century CE. It was during this time that Angkor finally gained significant control over the network of Si Mahosot and probably expanded their territory to the core of Dvāravatī in central Thailand. This frontier – and its putative borderline – was never stable and shifted depending on the push and pull of political powers to the east and west.

The study of frontiers is not widespread in Southeast Asian archaeology. This paper has demonstrated the significance of turning our attention away from the cores and capitals of its early states. Eastern Thailand represents an important area of multiculturalism and negotiation between two of the region's most influential states. The variety of architectural and sculptural styles, along with the hybridity of culture, allowed for the creation of a truly local style. Political influence and potentially occupation by Dvāravatī and Angkor served to modify the material record, but it remains unique from other parts of the region in terms of urban forms and types of ponds. Continued research in these peripheral zones will hopefully identify further examples of cultural diversity within the rich tapestry of Southeast Asia's early history.

Author agreement statement

This statement is to certify that all authors have seen and approved the manuscript being submitted, have contributed significantly to the work and agree to its submission to the journal of Archaeological Research in Asia.

We attest that the article is the Authors' original work, has not received prior publication and is not under consideration for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

Patcharaporn Ngernkerd: Writing – original draft, Methodology, Conceptualization. **Rasmi Shoocongdej:** Writing – review & editing, Supervision, Conceptualization. **Saritpong Khunsong:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Patcharaporn Ngernkerd reports financial support was provided by The Royal Golden Jubilee Ph.D. Program of National Research Council of Thailand. Saritpong Khunsong reports a relationship with National Research Council of Thailand (NRCT) and Ministry of Higher Education, Science, Research and Innovation of Thailand that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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